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O. P. Naumkin, V. T. Terekhova and Ye. M. Savitskiy

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ABSTRACT

The phase diagram of the Al-Sc system is plotted for all concentrations. This diagram has the following basic features: There is no limit to the mutual solubility of aluminium and scandium in the molten state; four chemical compounds are formed in the system: $ScAl_3$, $ScAl_2$, ScAl and Sc_2Al; a peritectic transformation is observed on the aluminum side at 665°C with a composition close to pure aluminum, while there is a eutectic transformation on the scandium side at ~ 87 at. % Sc and 945°C; the solubility of scandium in aluminum at room temperature is ~ 0.5 at. %, while that of aluminum in scandium is ~ 4.0 at. %. The effect of scandium on the mechanical properties of aluminum is studied at room temperature and higher. It is found that scandium is more effective than other rare earth metals in strengthening aluminum.

Metallic scandium is an interesting rare earth metal with physical and /176* chemical properties which have been intensively studied in recent years (refs. 1-10). While the fundamental physical properties of metallic scandium have been

*Numbers given in margin indicate pagination in original foreign text.

studied in some detail, scandium alloys have received little attention. Only fragmentary data have been published in the literature on the interaction between scandium and elements in the periodic system, and only three complete binary phase diagrams have been published up to the present: Sc-Ti (ref. 9), Sc-Zr and Sc-Y (ref. 10).

Continuous series of solid solutions in both the α-and β-modifications of both components are characteristic of the Sc-Zr and Sc-Y phase diagrams. The Sc-Ti phase diagram shows a continuous series of solid solutions in the β-modifications of both components as well as two-phase regions at room temperature.

Al-Sc alloys have not been studied up to the present time[1].

An analysis of Mott and Hildebrand miscibility factors in the liquid state indicates that scandium should mix with aluminum in the liquid state throughout the entire concentration interval (ref. 12). The considerable difference in the electronegativity of these two elements indicates that there may be chemical compounds in the system.

Some properties of scandium and aluminum are given in the table.

SOME PROPERTIES OF SCANDIUM AND ALUMINUM

Metal	Melting point °C	Polymorphic conversion point °C	Atomic diameter Å	Type of crystal lattice	Electro-negativity	Valence
Sc	1535	1350	3.28	α-Sc-close-packed hexagonal face-centered cubic	1.27	3
Al	660	-	2.86		1.48	3

[1]Data published in reference 11 relating to the effect of scandium on the mechanical properties of aluminum were the preliminary results of the present work.

Materials and Methods used in the Studies

Distilled 99.5% pure scandium was used for constructing the Al-Sc phase diagram (Be≤0.001, Si≤0.001, Ti≤0.1, Al≤0.01, Ca-0.01, Fe-0.06, Cu-0.15, N_2-0.03, O_2-0.2, H_2-0.01, C-0.0079 wt. %, Zr, Mo, Ta-indetectable), and commercial 98.16% pure scandium was used for studying the mechanical properties of the alloys (Si≤0.05, Yb≤0.05, Y-0.05, Th≤0.1, Ti≤0.05, Al≤0.01, Mo≤0.01, Ca-0.037, Fe≤0.05, C-0.16 wt. %, Be, Zr, Ta-indetectable). In addition, grade AV000 aluminum was used in all cases (99.99 wt. % Al).

The phase diagram was constructed on the basis of alloys prepared in an electric-arc furnace with permanent tungsten electrode on a water-cooled copper sole in a purified helium atmosphere at a residual pressure of 200-300 mm Hg.

The alloys used for determining the mechanical properties were melted /177 in an electric resistance furnace in corundum crucibles. Because of the considerable difference in the melting points of aluminum and scandium, the scandium charge was wrapped in aluminum foil and added to the molten aluminum which had been heated to 1000°C. The alloy was held at this temperature for 20-40 minutes and mixed with a tungsten rod. The alloys were teemed into copper molds 20 mm in diameter after fusion.

The alloys were homogenized by annealing in evacuated quartz ampules. The alloys were wrapped in tantalum or molybdenum foil to keep the specimens from interacting with the quartz. Alloys containing up to 25 at. % Sc were annealed at 550°C for 240 hours, alloys with a scandium content from 25 to 65 at. % were annealed at 1000°C for 100 hours and the remaining alloys were annealed at 850°C for 100 hours. In all cases, the specimens were gradually furnace-cooled after holding at the given temperature.

Bars made of the alloys for measuring mechanical properties were forged at room temperature on mandrels from 20 mm to 6 mm in diameter. Standard tensile specimens were cut from the deformed metal with a test diameter of 3 mm. The specimens were tested on a Gagarin press at a deformation rate of 0.16 mm/min at 20, 100, 200, 300 and 400°C.

Al-Sc Phase Diagram

Forty alloys were prepared and studied for constructing the phase diagram. The general form of the diagram is shown in figure 1.

Aluminum and scandium fuse in the molten state at all concentrations.

A characteristic feature of this diagram is the formation of 4 chemical compounds: $ScAl_3$, $ScAl_2$, ScAl and Sc_2Al. There are two eutectic transformation in the system: Zh⇌Sc_2Al+α-Sc (at ~ 87 at. % Sc and 945°C) and Zh⇌$ScAl_2$+ScAl (at ~ 43 at. % Sc and 1150°C).

On the aluminum side, a peritectic is formed which approaches pure aluminum in composition at a temperature of 665°C.

The microstructures of annealed alloys are shown in figures 2 and 3. The microstructures of alloys with compositions close to the chemical compounds $ScAl_3$, $ScAl_2$, ScAl and Sc_2Al are shown in figures 2c, d, f and g. All alloys approach the single-phase state. It may be assumed on the basis of microstructural and thermal analysis that all the compounds listed above have narrow intervals of homogeneity since segregation of a second phase is observed /178 when there is a slight deviation from the stoichiometric composition.

Data of thermal analysis were used to establish the temperatures at which chemical compounds are formed by peritectic reactions. These temperatures are 1330±7 and 1195±7°C for $ScAl_3$ and Sc_2Al respectively. The compounds $ScAl_2$ and ScAl melt congruently at ~ 1420 and ~ 1300°C respectively. The peritectic /179

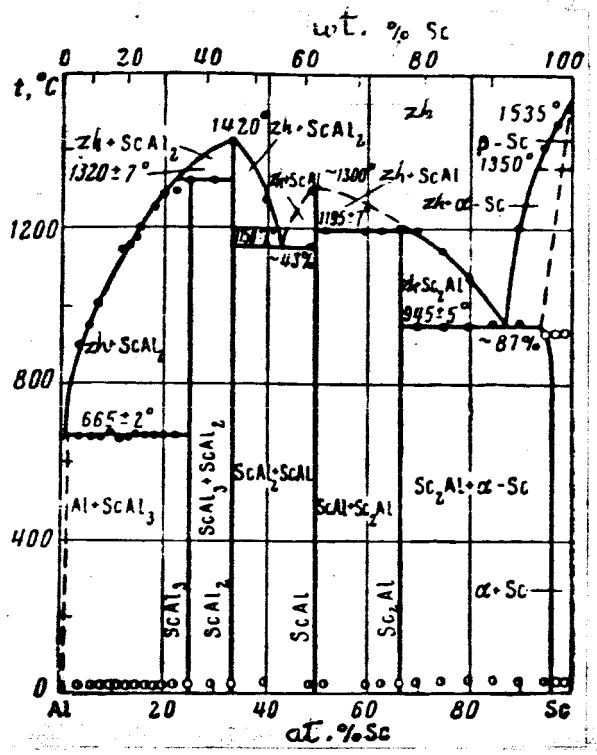

Figure 1. Phase diagram of the Al-Sc system

reaction temperature is 665±2°C which is only 5° higher than the melting point of pure aluminum.

All chemical compounds in the Al-Sc system are extremely brittle and crack even as the alloys are solidifying on the water-cooled sole after melting in the arc furnace. The chemical compounds $ScAl_3$, $ScAl_2$, ScAl and Sc_2Al have microhardnesses of 255, 530, 370 and 460 kg/mm^2 respectively.

Solubility of scandium in aluminum in the solid state at room temperature was determined by microstructural analysis and measurement of the microhardness and electrical conductivity. According to these data, the solubility of scandium in aluminum at room temperature is ~ 0.5 at. % Sc (~ 0.83 wt. %).

The solubility of aluminum in scandium at room temperature was found to be ~ 4.0 at. % (~ 2.4 wt. %). The solubility of aluminum in scandium increases with temperature. A scandium alloy with 5 at. % Al showed a single-phase microstructure after quenching from 900°C.

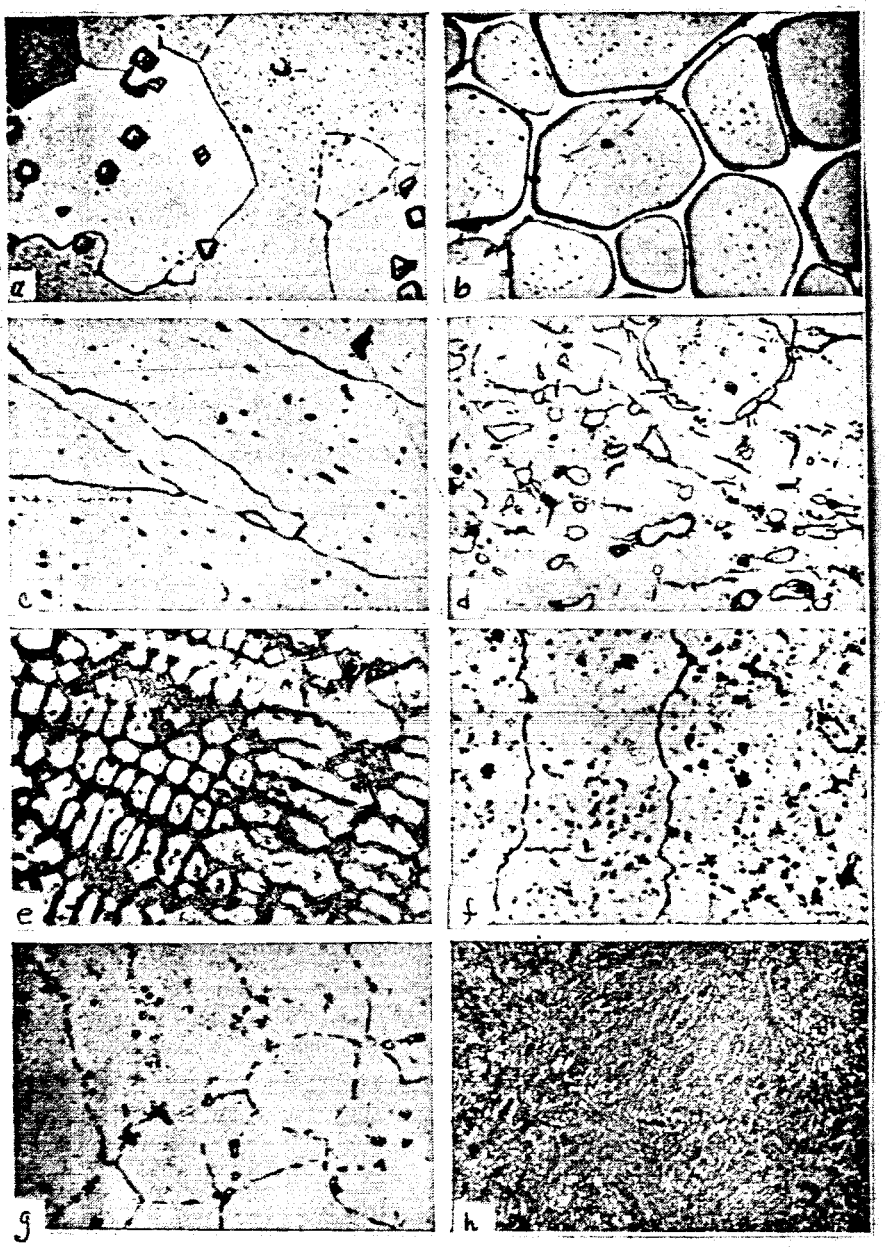

Figure 2. Microstructures (X500) of annealed alloys in the Al-Sc system (electrolytically polished and etched): a-Al+1.0 at.% Sc ($Al+ScAl_3$); b-Al+20.0 at.% Sc ($Al+ScAl_3$); c-Al+25.0 at.% Sc ($Al+ScAl_3$); d-Al+32.0 at.% Sc ($ScAl_3+ScAl_2$); e-Al+40.0 at.% Sc ($ScAl_2+ScAl$); f-Al+52.0 at.% Sc ($ScAl+Sc_2Al$); g-Al+66.7 at.% Sc (Sc_2Al); h-Al+85.0 at.% Sc (Sc_2Al+Sc).

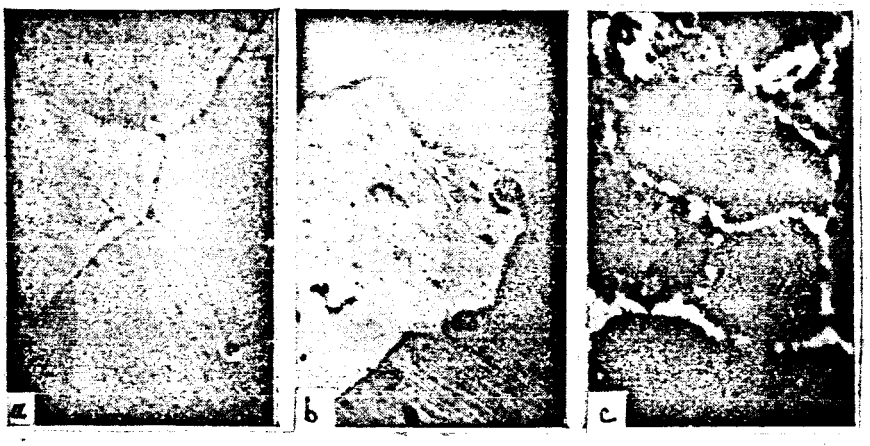

Figure 3. Microstructures (X500) of annealed scandium-rich Al-Sc alloys photographed in polarized light: a-Sc, initial; b-Al=98.0 at.% Sc (Sc-solid solution); c-Al+95.0 at.% Sc ($Sc+Sc_2Al$).

X-ray analysis of alloys in the aluminum-scandium system[2] confirmed the Al-Sc phase diagram given in this paper. Detailed results of the X-ray structural study will be published.

Effect of Scandium on the Mechanical Properties of Aluminum

Results of the measurement of mechanical properties are given in figure 4. These data show that additions of scandium to aluminum even in quantities below 0.7 at.% increase the braking point of aluminum at room temperature with no noticeable reduction in ducitility. An addition of 0.7 at.% Sc increases the tensile strength of deformed aluminum by nearly 10 kg/mm^2. These alloys maintain a relatively high strength up to 200°C. A reduction in strength is observed at temperatures close ~~at~~ to 300°C.

A comparison of the data relating to the effect of scandium additions on the strength of deformed aluminum with previous results obtained in our /180

[2]Analysis was done in collaboration with R. N. Kuz'min (Moscow State University).

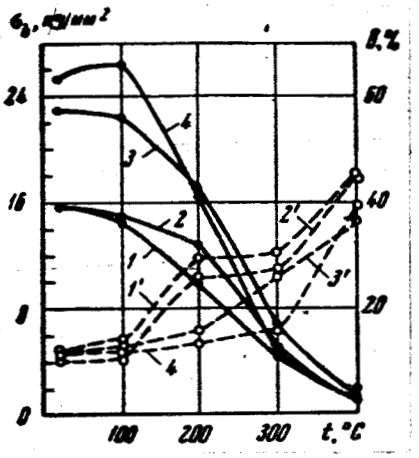

Figure 4. Effect of scandium of σ_b (solid lines) and δ (broken lines) in aluminum at various temperatures (1, 1'-pure aluminum; 2, 2'-addition of 0.1 at.% Sc; 3, 3'-0.3 at.% Sc; 4, 4'-0.7 at.% Sc)

laboratory on the effect of cerium, lanthanum, neodymium and yttrium shows that scandium is more effective than any of the other rare earth metals studied in strengthing aluminum. This is probably due to the fact that scandium is considerably more soluble in aluminum in the solid state than the other rare earth metals.

Discussion of Results

Although scandium is considered a rare earth metal, it has many properties which set it apart from these metals.

A comparison of scandium with rare earth metals from the standpoint of physicochemical behavior is necessary as a first step toward explaining the nature of alloy formation in metallic scandium.

The process of alloy formation in scandium is affected by a number of its properties (type of crystal lattice, electornegativity and valence) which are close to the properties of rare earth metals. The basic differences between

scandium and the rare earth metals are the absence of 4f-electrons in scandium and the considerable difference in atomic radii (fig. 5).

Scandium and yttrium are analogs of the rare earth metals. Although the dimensions of the lanthanum atom are considerably greater than those of yttrium, the atomic radii of the following rare earth metals are reduced by "lanthanide compression" to the size of yttrium atoms in the gadolinium-terbium intergal. The small difference between atomic dimensions together with the similarity in outer electron shells explains the natural occurrence of yttrium in combination with rare earth metals in the yttrium subgroup as well as the striking similarities in solubility of the crystal structure and general chemical properties of compounds. However, "lanthanide compression" is not enough to reduce the dimensions of atoms and ions of the rare earth metals to the corresponding dimensions in scandium. Therefore the chemical properties of scandium as well as a number of its physical properties set it apart from the other rare earth metals.

Since scandium atoms are considerably smaller than those of the rare earth metals, this element is generally much more soluble than the other rare earth metals in most elements of the periodic system, and sometimes even forms continuous series of solid solutions.

The ability of scandium to form solid solutions may be clearly seen from an examination of the combined effect of electronegativity and the dimensional /181 factor (solubility graphs (refs. 12, 13)). A graph of this type for metallic scandium is given in figure 6. The atomic radii of the elements are given along the horizontal axis and the electronegativity is plotted along the vertical axis. Auxiliary ellipses are constructed to determine the limits of solubility. The inner ellipse has a major axis of ±0.2 electronegativity unit and a minor axis of ±8% of the difference in atomic radius while the outer ellipse is constructed

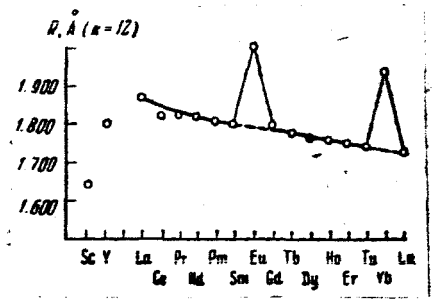

Figure 5. Atomic radii of the rare earth metals

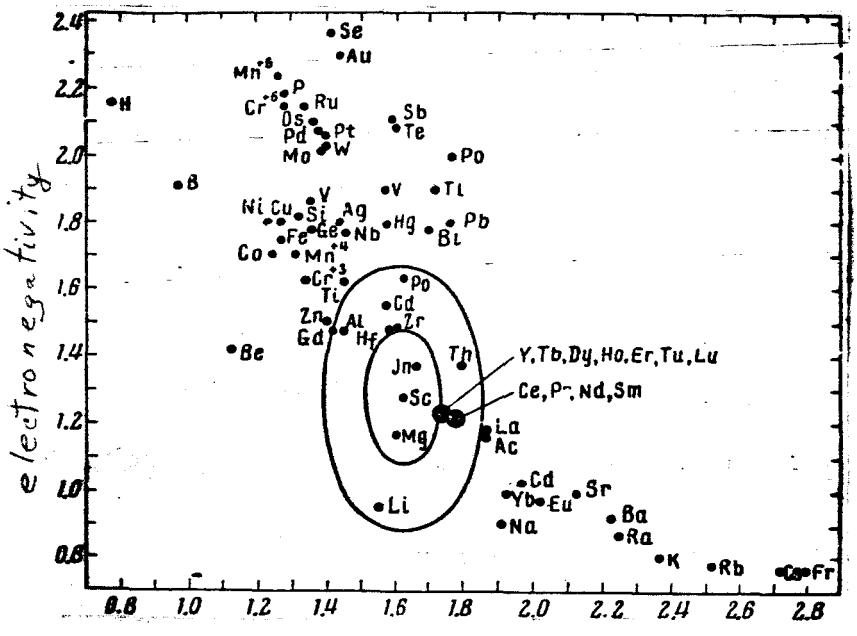

Figure 6. Solubility graph for scandium

with dimensions of ±0.4 electronegativity unit and ±15% of the difference in atomic radius. Metals which have favorable factors for the formation of a wide region of solid solutions should lie within the smaller ellipse. Limited solid solutions predominate in the ring between the large and small ellipses, while dimensional and electrochemical factors do not favor the formation of solid solutions beyond the confines of the large ellipse.

The graph in figure 6 shows that scandium occupies an isolated region far removed from most industrially important metals. Scandium may form wide regions

of solid solutions with magnesium, indium, rare earth metals, α-zirconium, hafnium, palladium, tin, cadmium, lithium, thorium, actinium and americium. Scandium should form only extremely small regions of solid solutions with other metals.

Ample experimental data have already confirmed this hypothesis. Scandium (in the α- and β-modifications respectively) forms a continuous series of solid solutions with α- and β-zirconium. Scandium has a maximum solubility of ~ 32 wt.% in magnesium, while the solubility of yttrium in magnesium is ~ 9.0 wt.% and the solubility of other rare earth metals is only 1-2 wt %.

The difference between scandium and the rare earth metals also shows /182 up in the Al-Sc phase diagram. All rare earth metals form a eutectic on the aluminum side, while peritectic decomposition takes place in the Al-Sc system.

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